FINAL REPORT

EETF GRANT NUMBER: 7310035
High Capacity Airborne Wind Turbine
Altaeros Energies
9/30/2016

Project Summary

The objective of this EETF Grant Project was to demonstrate the potential for a novel Buoyant Airborne Turbine (BAT) to generate electricity to support local infrastructure and reduce the burden of high fuel costs in rural communities. The BAT uses a helium-filled inflatable shell to lift a lightweight turbine 500 to 2,000 feet above ground, where winds are stronger and more consistent than those reached by traditional, tower-mounted wind turbines.

The project successfully identified a test site at the Eva Creek wind farm and electrical interconnection partner through the Golden Valley Electric Association, and gained initial favorable environmental approvals. In addition, the project demonstrated the feasibility of stable, automated deployment of the airborne platform up to 800 ft above ground level. Finally, the project demonstrated the design feasibility of the airborne wind turbine system.

The project was stopped earlier than originally planned without completing all of the project milestones, including the full-scale airborne testing of the complete airborne wind turbine system. The main drivers of this were challenges obtaining FAA approval for the specific project site and nighttime operations, changing market conditions, and delayed development.

Overview of Planned Milestones and Results

Task		Deliverables	Status
1	Final site selection, permitting, and community forum	Site agreement, interconnect agreement, FAA permit, USFWS permit	Site and verbal interconnect agreement in place with GVEA pending FAA and Board approval
2	30kW turbine assembly and testing in Maine	Turbine test results	Progressed through initial design phase
3	Complete instrumentation plan and shakedown test plan	Instrumentation plan and testing plans	Internal plan completed for 2013 flight platform prototype (without turbine)
4	Safety and shakedown testing and performance validation in Maine	Report summarizing testing results, baseline turbine performance curve, and anemometer validation	Underwent testing of flight platform without turbine in Limestone, ME (Fall 2013, Fall 2015) and Southern New Hampshire (Summer 2016).
5	Transport BAT trailer and container to site		Did not start
6	BAT final assembly and on-site performance test		Did not start
7	Electrical interconnection complete		Did not start

8	BAT launch and commissioning testing	Commissioning report	Did not start
9	18 months of BAT operation and monitoring		Did not start
10	Data evaluation		Did not start
11	Draft project report	Draft project report	Did not start
12	Final project report	Final report	Complete

Task 1:

Site selection

Altaeros Energies, TDX Power, and project consultant Tom Lovas worked together to identify 15 potential sites for the project. The team evaluated sites on a 6-variable matrix to rank order them, seen in Figure 1.

Site Selection - Altaeros 30kW Wind Turbine

		Selection Criteria [Score 1 (low) to 4 (high)]						
Possible Locations	**Notes**	Ease of Permitting (FAA)	Ease of Site Prep: Interconn/terrain	Access from Anchorage	Community Acceptance	Ease of Install/O&M	Adjacent data for Benchmarking	**Total**
Delta Junction	Previous issue,	4	3	3	4	3	4	21
Eva Creek	Wind farms on	4	3	2	4	2	4	19
JBER Site Summit	Near Anchorag	3	4	4	3	3	2	19
Mat/Su Valley	Unknown , close to	2	4	4	3	4	2	19
Nikiski	Favorable interconn	2	4	3	3	4	2	18
Homer Hilltop		2	4	3	4	3	1	17
Seward		2	3	3	3	4	2	17
Bird Point		1	3	4	2	4	2	16
Fire Island		2	3	2	3	2	4	16
Portage Valley		1	4	4	2	3	2	16
Tok		2	3	2	4	2	2	15
Thompson Pass		1	3	2	3	3	2	14

Figure 1: Ranking of potential test sites.

The Altaeros project team travelled to Alaska in July, 2013, to visit and conduct a detailed evaluation of the top prospective sites. The ranking of potential sites is shown in Figure 1 and summary results for some of the higher scoring sites are provided below:

- Delta Junction – Very favorable visit and meeting with site owner. Specific site coordinates identified. Crucial issue to be evaluated is airspace permitting given airport within 5 miles.

- Eva Creek – Very favorable site visit and meeting with GVEA. Two potential site coordinates identified. GVEA gave full support for the project. Crucial issue to be evaluated is accessibility due to rail car required to transport to site.

- Murphy Dome – Site visit completed. Deemed less attractive due to difficulty of three obstructions at site: FAA equipment, Air Force Dome, and 100ft communications tower.

- JBER – After speaking with military rep, deemed less attractive due to visibility from Anchorage, lack of military support, and challenge deploying at an active base.

- Mat-Su Valley – Site visit completed. Deemed less attractive due to visibility from Anchorage and interference with ski resort at all appropriate locations.

Eva Creek was selected as the preferred test site, based on benefits of partnership with the Golden Valley Electric Authority (GVEA) and the prior FAA approvals of the existing wind turbines on-site. In addition this site would allowed comparison of test data to nearby conventional wind turbines, and had electrical connections and on-site maintenance staff that would benefit the project. Altaeros worked with Paul Morgan at GVEA to identify a specific site location. The project was to be presented to GVEA Board for formal approval and interconnection plan following FAA approval. The preferred test site within Eva Creek, and a layout of the Eva Creek wind farm are shown in Figures 2 and 3, respectively.

Figure 2: Preferred test site, southwest of Turbine 9 at Eva Creek wind farm.

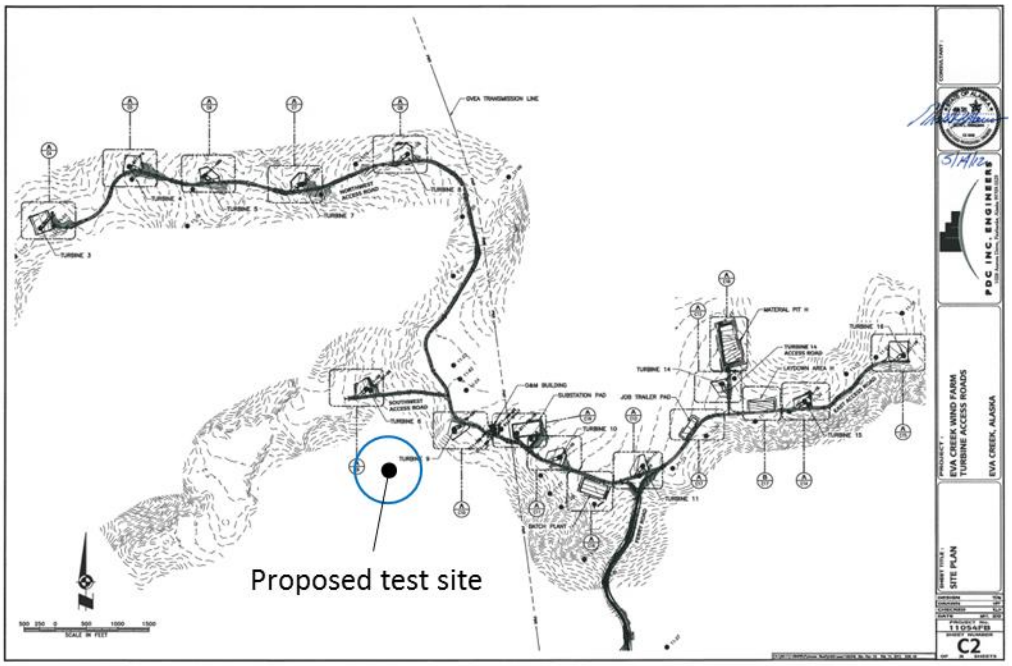


Figure 3: Layout of Eva Creek wind farm with proposed test site.

Permitting

An Environmental Assessment of the Altaeros Airborne Wind Turbine was completed by Normandeau Environmental Consultants. The report concluded: "Using best professional judgment based on our experience with conventional land-based wind turbines and the information available at this time, Normandeau Associates concludes that, on average, the deployment of the AWT is likely to have equal or lesser overall environmental impact than the deployment of tower-mounted wind turbines of similar size." The two largest environmental impacts to mitigate were deemed to be airspace interference with low flying aircraft, and potential impact of the tethers on migratory birds.

A phone call was also held on July 10, 2013 with the US Fish & Wildlife Service (USFWS) at AEA offices. The USFWS representative indicated that no material impact was expected, especially if project was sited at existing Delta Junction or Eva Creek wind farms, that were deemed to have limited avian impact. If deployed at Eva Creek, the team planned to check eagle nesting locations to minimize potential impact.

After numerous iterations due to the unique nature of the project, Altaeros submitted an application to the FAA on April 29, 2014 and June 22, 2015 for an obstruction evaluation. The application was reviewed by all divisions of the FAA's Obstruction Evaluation Group and a 'Notice of Presumed Hazard' was given, prohibiting execution of the project plan. Specifically, the site's proximity to a nearby non-operational airstrip is too close given the proposed turbine operating altitude of 1,000 ft.

A follow up conversation on December 1, 2015 with the group also revealed that a full-day operating permit would not be granted until there is guidance given by the national FAA office on marking and lighting for airborne wind energy systems. The FAA advised it was unlikely that any guidance from the national office would be delivered by the end of 2016. This news was unexpected and is related to an FAA evaluation currently being done of another airborne wind energy technology.

Community Assessment

Due to the delay in FAA permitting, the site selection was never finalized and the community assessment was never formally completed. The project was featured on the front page of the New York Times business section on May 20, 2014, and featured in the Fairbanks News Miner on March 31, 2014. A video designed to educate the public about the technology was featured in over one hundred publications and viewed almost one million times by the public (video can be seen at http://youtube.com/watch?v=kldA4nWANA8).

Task 2: 30kW turbine assembly and testing

Task 2 progressed through the initial design phase of the 30kW wind turbine, including component level design and testing. The primary objective of the wind turbine effort was to develop and demonstrate an ultra-lightweight wind turbine that could be lifted by the inflatable lifting platform. The emphasis on low weight drove several key design aspects, and required a novel approach compared to most commercially available turbines.

Generator:

Altaeros worked with an initial generator vendor to develop a lightweight, high voltage, large radius permanent magnet, direct drive (PMDD) generator. A 6 kW scale prototype generator was built and tested, shown in Figure 4. Results from the generator test, shown in Figure 5, confirmed zero-load characteristics, including a phase-to-phase voltage of 500 and frequency of 350 Hz. The high voltage and frequency are required to maintain low weight in the rest of power conversion and transmission system. Full load testing was not completed due to faulty wiring in one of the windings.

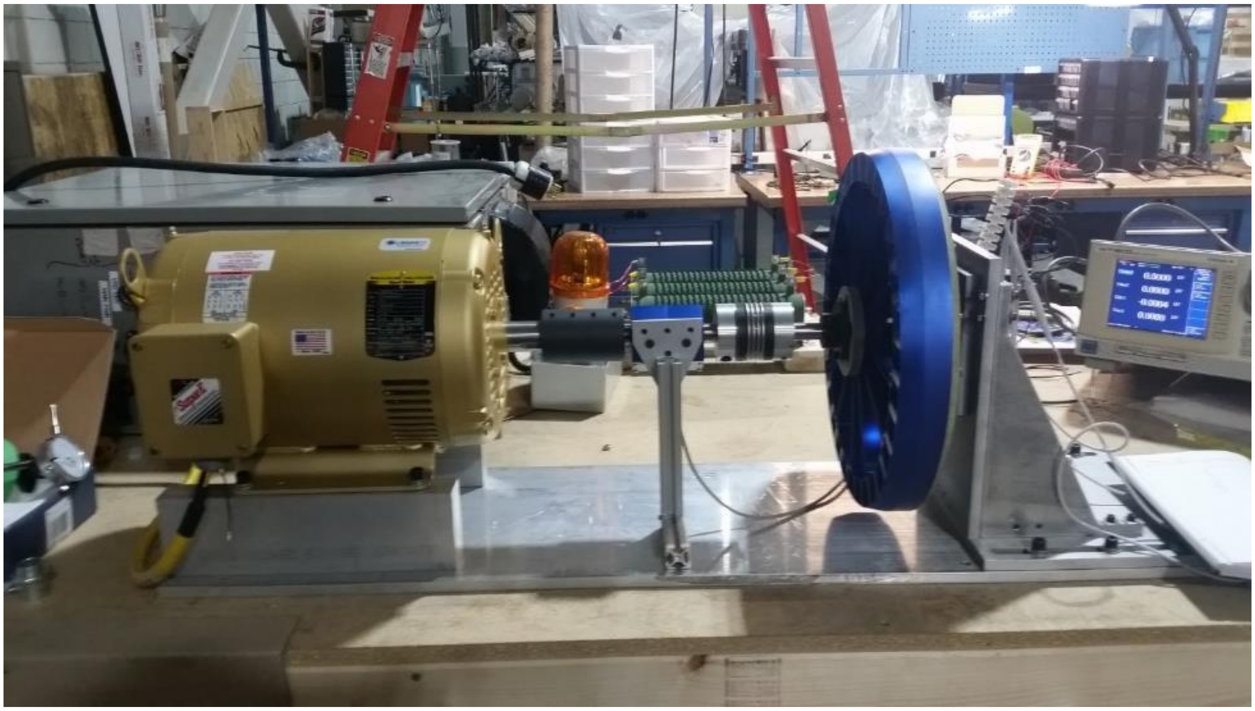
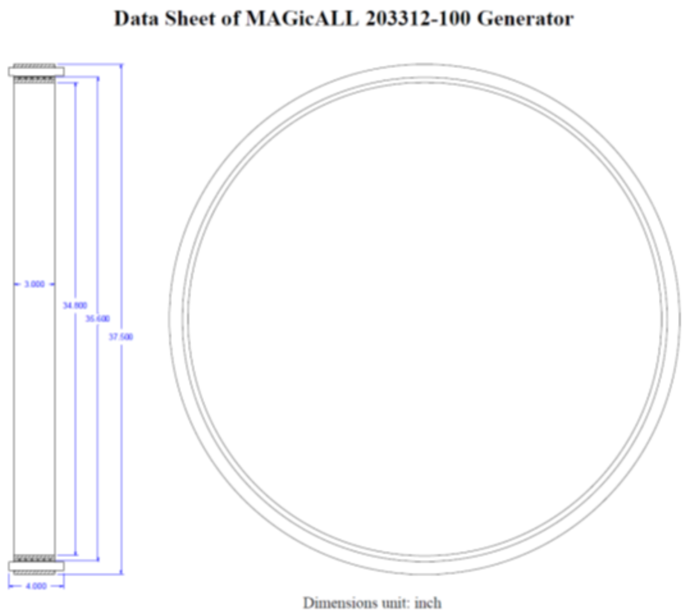


Figure 4: 6 kW scale generator on dynamometer test fixture.

Figure 5: 6 kW scale generator measured phase-to-phase voltage trace at zero load.

A preliminary design and specification was developed for the full scale generator and power conditioning architecture, shown below in Figures 6 and 7. Due to other delays in the turbine development, the full-scale generator and power conditioning system were not built and tested.



Power, kW	35.0
Speed, RPM	200
Voltage_LL, Vrms	480
Frequency, Hz	400
Stator OD, in	37.50
Stator ID, in	35.70
Air gap, in	0.05
Rotor OD, in	35.60
Rotor ID, in	34.80
Stack length, in	3.00
Total length, in	4.00
Power factor	0.90
Efficiency, %	94.1%
Min. cooling air speed m/s	10
Weight, kg	52.5

Figure 6: Full scale generator preliminary design and specification

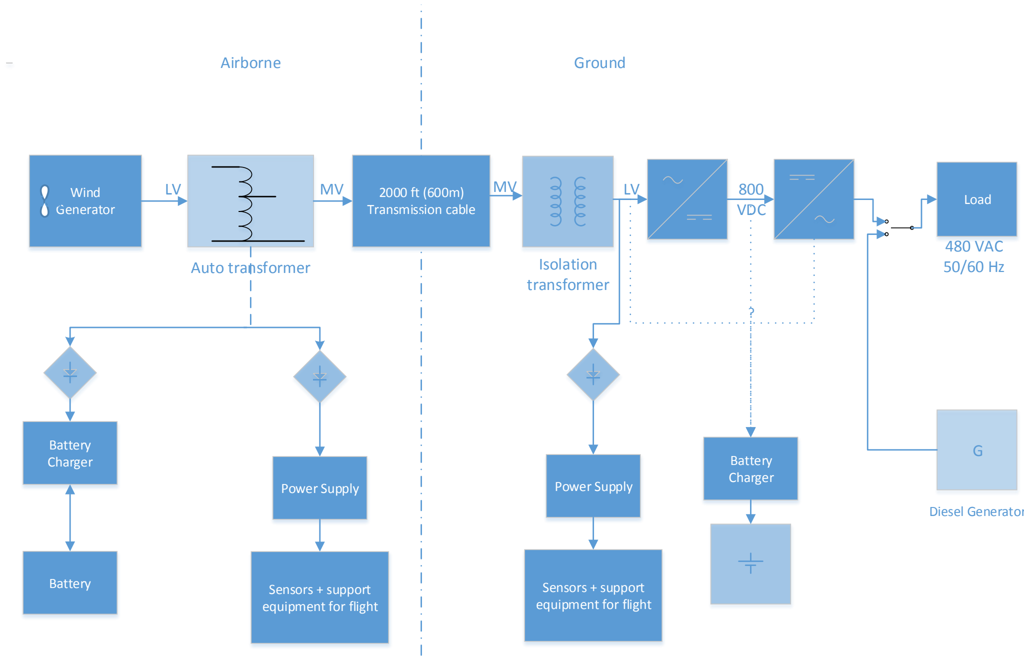


Figure 7: Power conditioning system architecture.

Nacelle:

Altaeros worked with a third party wind turbine design firm to develop a preliminary design for the nacelle/frame. The design includes a mounting disk and fixed external frame for mounting the stator and attaching the full assembly to the aerostat; an external disc brake for emergency stopping; and a main shaft and stator mounting. A cut-away view and initial finite element analysis (FEA) calculation of deflection under load for the preliminary nacelle design is shown in Figure 8.

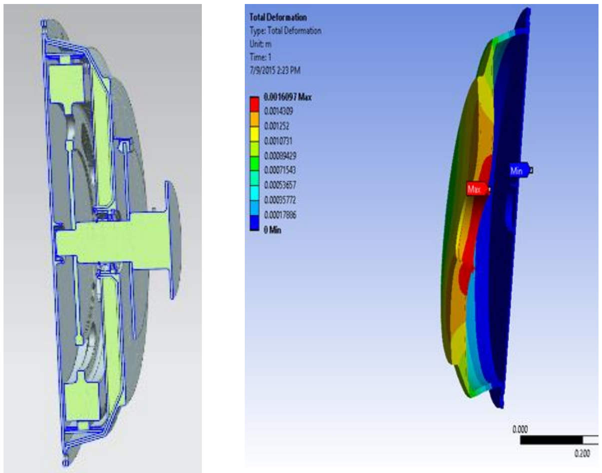


Figure 8: A cut-through view of the preliminary nacelle design (left) and FEA analsys of deflection under worst case loading.

System Architecture:

In 2015, high level and customer driven system requirements and architecture were developed for the overall wind turbine system. After completing the initial trade study with our initial third party wind turbine design firm, several major risks and concerns were raised by other third party wind turbine advisors. Based on the input from these advisors, Altaeros conducted an internal study of turbine architectures and concluded that the stall control architecture recommended by our initial turbine design firm required very high weight components to mitigate control risks. As can be seen in Figure 9, increasing Tip Speed Ratio (λ) for stall control turbines leads to a higher max torque, which occurs at higher wind speeds. In order to control speed, the generator needs to be sized to provide this max torque (or a brake system capable of partial braking for speed control must be used).

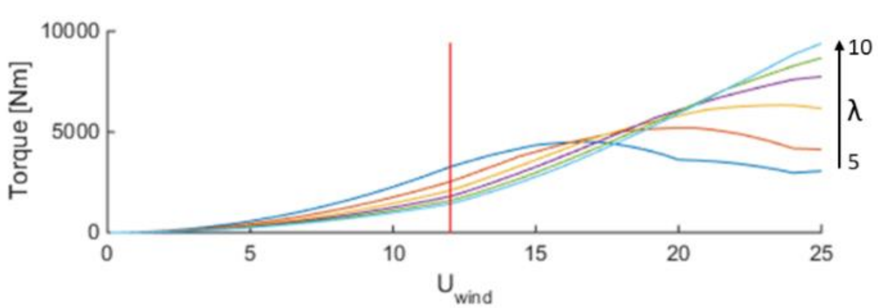


Figure 9: Torque speed curves for stall controlled turbines with Tip Speed Ratios ranging from 5 to 10. While rated torque decreases with increasing λ, peak torque increases.

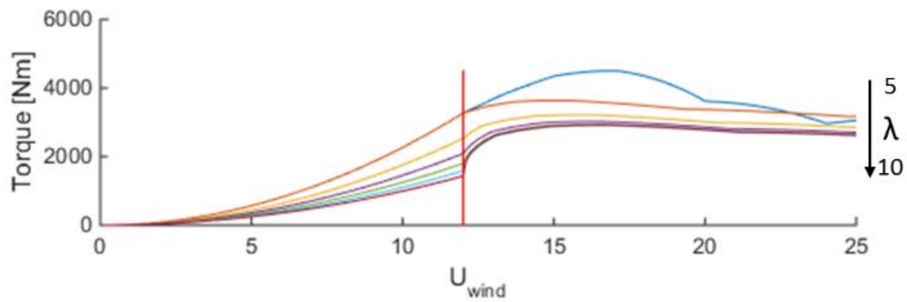


Figure 10: Torque speed curves for pitch controlled turbines with Tip Speed Ratios ranging from 5 to 10 (compared with a stall control turbine with λ=5, in blue). Higher λ leads to lower peak torque.

In contrast, a pitch controlled turbine with active torque control results in a significantly lower peak torque, allowing for a reduced weight drivetrain throughout. This trend is shown in Figure 10. The internal architecture study concluded that a pitch control turbine was the preferred path forward for an ultra-lightweight wind turbine at the size ranges under consideration. As a result of this study, it was clear that significant rework was needed to mitigate a risk of control failure inherent in the initially recommended design approach. This finding contributed significant delay in the development of the turbine, and led to the flight platform tests proceeding without the turbine component.

Task 3: Complete instrumentation plan and shakedown test plan

An internal instrumentation and shakedown test plan was completed to support Altaeros' internal testing of the 2013 flight platform. This test plan is included as part of the test report in Appendix A. The test plan did not include the turbine component due to delays in the turbine development effort, and was thus not included in the AEA grant.

Task 4: Safety and shakedown testing and performance validation

Altaeros proceeded to test a number of airborne platform prototypes without the turbine component in order to validate performance across a number of conditions. Three of these systems are shown in Figure 11. The design tested in 2013 (left) exhibited satisfactory performance but was determined to be too expensive to fabricate to offer a competitive energy solution. As such, the design evolved into a more traditional teardrop shaped aerostat, as shown in the prototypes tested in 2015 (middle) and 2016 (right).

Figure 11: Three Altaeros prototype platforms, tested in 2013 (left), 2015 (middle) and 2016 (right).

All three of the prototype platforms shown in Figure 11 were equipped with airborne anemometers/weather stations, an inertial measurement unit, pressure transducers and load transducers. Measured performance of the flight system was compared against a 6 Degree-Of-Freedom model. An example comparison of logged XYZ position measurements and 6DOF simulation results of the 2016 prototype and simulation data is shown in Figure 12.

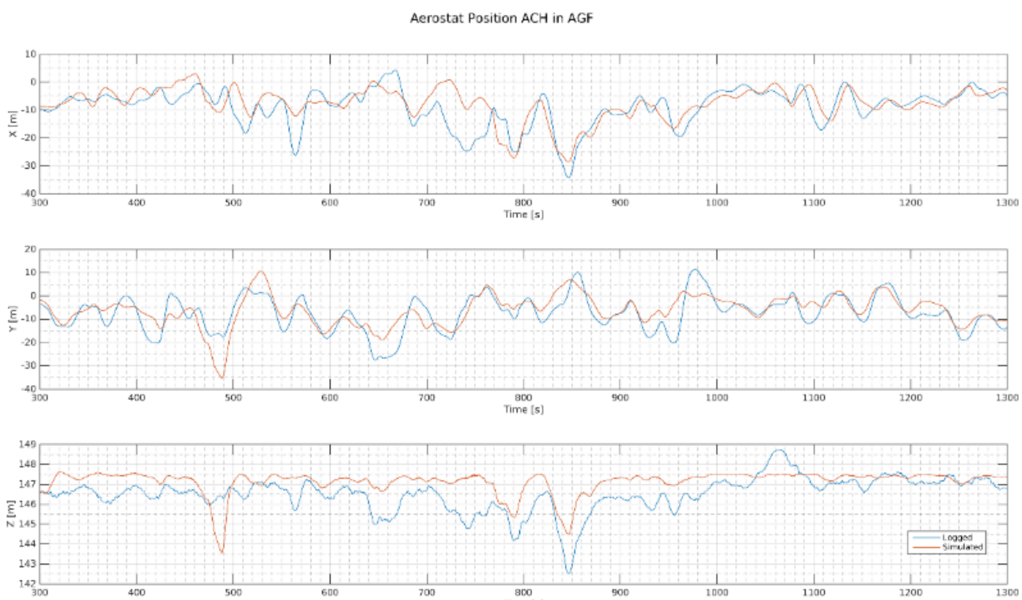


Figure 12 Logged XYZ position measurements compared with simulation results for the 2016 flight platform prototype

Over 120 experiments were performed, in Maine and New Hampshire, throughout the shakedown testing of the flight platform prototypes between 2013 and 2016. Results from the initial testing are included in Appendix A. During these tests a number of variables were adjusted, including center-of-mass location, tether attachment locations and fin trim angles. A summary of statistics from these tests is below:

Test days	46	
Flight time	96	hours
Maximum altitude	150	meters
Maximum wind speed	20.3	m/s
Top mean wind speed	12	m/s

Shakedown test results indicate that the preferred configuration of center-of-mass, tether attachment and fin settings results in stable airborne operation across a wide range of environmental conditions.

Other Tasks:
Other tasks were not started, as Altaeros and the AEA jointly decided to prematurely close the grant project, due to ongoing delays and continued permitting uncertainty. Therefore, the bulk of the data collection plan, which was designed for Tasks 5-10 and related to energy production, was not completed.

Summary

Throughout the project period, the project team achieved a number of successes and faced a number of challenges. They key successes of the project include:

- *Site selection and interconnect partner*. The Eva Creek site proved to be an excellent site for testing novel, innovative energy solutions, in large part due to the support of the GVEA. The presence of existing wind turbines and associated energy infrastructure lessened the burden of site preparation, and provided a great opportunity to compare performance against the current standard wind technology.
- *Risk mitigation*. The project team identified key turbine technical risks prior to expensive build and installation. The significant technical risks associated with developing an ultra-lightweight wind turbine with sufficient control authority to ensure safe operation was identified prior to significant project resources were expended on building the initial turbine prototype.
- *Stable airborne platform*. Altaeros has continued to make progress on developing a low cost, autonomous flight platform that forms the core of the BAT product.

In August 2016, following partial completion of the project tasks, and after several delays to the project timeline, Altaeros and the AEA jointly decided to close the EETF Grant for High Capacity Airborne Wind Turbines. Several factors contributed to this decision, including:

- *FAA airspace permitting*. Altaeros was aware of the small airstrip located several miles from the Eva Creek wind farm. Based on the very low utilization of the airstrip, and the fact that the wind farm had previously attained approval from the FAA, Altaeros did not expect the airstrip to be a significant barrier to obtaining an airspace waiver. This assumption was incorrect, and resulted in significant permitting challenges. These permitting challenges were further aggravated by the decision of the local FAA to not treat the BAT as a standard moored balloon, but rather to wait national guidance on treatment of airborne wind energy systems.

- *Turbine component development*. The development of the lightweight wind turbine component was delayed to ensure that all control risks were mitigated.
- *Changing market conditions*. Market pressures from a drop in oil prices of over 50 percent since grant initiation in 2013 made a 30kW BAT less competitive in off-grid environments, and emphasized the need to focuses resources on other sources of revenue from the platform beyond energy.

Future Actions

Altaeros continues to believe that the compelling advantages of airborne wind turbines are uniquely well suited to address the challenges faced by rural Alaskan villages. While many parts of Alaska, especially the coastal regions, have a strong wind resource, the same logistical challenges that make diesel generation incredibly expensive also drive up the cost of traditional, materially intensive ground-based wind turbines and other renewable energy generators. In contrast, airborne wind turbines are inherently material efficient because they harness an energy source with nearly 8X greater power density than typical tower-mounted turbines, while eliminating the heaviest and most logistically difficult components of traditional wind turbines (eg. towers and foundations). During the course of this project we received an unsolicited email with encouragement and support from an Alaska resident who lives in a rural village outside Bethel. He perfectly summarized the reasons why airborne wind is a great potential solution for Alaska:

> *"The problem with wind here is that for 5 months of the year, especially where I live in old Kasigluk, it is basically a swamp. You literally cannot walk on dry ground in the summer. You go from house to house or the school all on boardwalks. There is land, but you need boots on to walk on it. So traditional turbines require a gigantic concrete foundation. And all that material (concrete, steel, tower, turbine blades, etc) has to be flown or barged in, which is crazy expensive. So of course your idea…sounds perfect!"*

We encourage the AEA to follow the progress of airborne wind turbine concepts, which may offer another avenue to reduce energy costs for rural Alaskans. This project revealed a number of lessons in pursuing similar projects in the future:

- Partners and community members were open and receptive to potential for novel wind technologies to offer cost savings and other benefits to the community.
- Airspace permitting is a critical potential roadblock for this technology, and thus should be secured as early in the project as possible. Nighttime marking and lighting, and proximity to airports, are the two main permitting risk areas.
- Due to volatility in oil & gas markets, airborne wind products that have multiple revenue streams, including energy, communications, security, and/or data monitoring, may be best positioned to deliver long term cost competitiveness.
- Technology development for large wind turbines has long design cycles, and thus the timeline for projects should be scoped appropriately.

APPENDIX A: 2013 Flight Prototype Test Plan and Report

The 2013 Flight Prototype Test Plan and Report is included as a separate attachment.